FERMILAB-Conf-01/011-E March 2001

Frascati Physics Series Vol. nnn (2001), pp. 000-000
HEAVY QUARKS AT FIXED TARGET - Rio de Janeiro, Oct. 9-12, 2000

QUARKONIUM PRODUCTION

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ABSTRACT

Results on the production of heavy Quarkonia (ψ and Υ families) from the HERA and Tevatron colliders are presented. The interpretation of the measurements in terms of perturbative QCD is critically reviewed.

1 Introduction

About 10 years ago, it was believed that inelastic J/ψ production at HERA would allow the precise determination of the gluon density in the proton, and diffractive J/ψ production was considered as a complementary way to measure luminosity. Today, there is no HERA measurement of $xg(x)$ using J/ψ, and probably little hope to obtain a competitive result in the foreseeable future. H1 and ZEUS measure $\int \mathcal{L}\, dt$ almost exclusively through the Bethe-Heitler process, with an excellent precision approaching 1 %.

On the other hand, the main questions in the field of Quarkonia today are much more interesting, and the amount of work that went into it is reflected in literally hundreds of experimental and theoretical papers: in short, is nonrelativistic QCD applicable to ψ production[1], and how well can diffractive vector meson production at HERA be understood in terms of perturbative QCD? In the following sections, I will give an overview of some important results obtained by CDF, H1, and ZEUS, and present examples from the literature about how the measurements can be understood in a QCD framework.

From 1992 to 1996, the CDF experiment at the Tevatron collected a data sample of $110\,\mathrm{pb}^{-1}$ of $p\bar{p}$ collisions at $\sqrt{s} = 1.8\,\mathrm{TeV}$ (Run 1). Besides excellent tracking and lepton ID, analyses at the Tevatron require good track impact parameter resolution in order to separate out the contribution from b decays. Measurements include the p_T dependence of the cross section, in a limited way the cross section as a function of the pseudorapidity η, and the vector meson polarization.

The HERA experiments H1 and ZEUS collected each more than $100\,\mathrm{pb}^{-1}$ of e^+p and e^-p collisions at $\sqrt{s} \simeq 300\,\mathrm{GeV}$ and $320\,\mathrm{GeV}$ in the years 1994 to 2000, a large fraction of which has not yet been fully analyzed. The range of measurements is much more diverse than at the Tevatron: "inelastic" and diffractive ("elastic" and proton diffractive dissociation) production can be separated using e.g. the elasticity variable $z := (p_\psi \cdot p_p)/(q \cdot p_p)$, where p_ψ, q and p_p denote the four-momenta of the ψ meson, the exchanged photon, and the incoming proton. Thanks to the overconstrained kinematics, cross sections are studied in terms of the virtuality of the photon $-Q^2$, the photon-proton centre-of-mass energy W, the transverse momentum p_T of the ψ, the elasticity z, and the helicity structure of the production process.

2 Production and Polarization of J/ψ, $\psi(2S)$ and Υ at the Tevatron

2.1 J/ψ and ψ(2S)

The CDF collaboration has previously reported results obtained from Run 1a data on the production of J/ψ and $\psi(2S)$ mesons [1, 2]. The measured cross sections for direct production were on the order of 50 times larger than predicted by the Colour Singlet Model [3]. However, calculations based on the

[1] In this paper, ψ is used to denote either J/ψ or $\psi(2S)$ mesons.

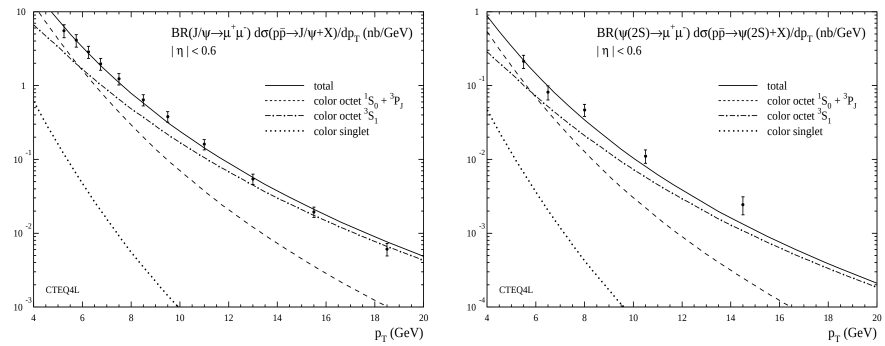

Figure 1: *Direct J/ψ and $\psi(2S)$ production cross sections from CDF as a function of p_T, for $|\eta^\psi| < 0.6$. The lines are the colour singlet prediction and fits of colour octet contributions. Figures from* [4].

nonrelativistic QCD (NRQCD) factorization formalism [5] are able to account for the observed cross sections by including colour octet production mechanisms. In this formalism, the production cross section for a Charmonium state, e.g. $A + B \to J/\psi + X$, can be expressed as

$$\sigma(A + B \to J/\psi + X) = \sum_n c_n(A + B \to c\bar{c}[n] + X)\langle 0|\mathcal{O}_n^{J/\psi}|0\rangle, \qquad (1)$$

where n denotes an on-shell $c\bar{c}$ pair in a definite colour, spin and angular momentum state. For each n, the cross section factorizes into a short distance part c_n calculable in a perturbative QCD expansion in $\alpha_s(2m_c)$, and a long distance matrix element $\langle\mathcal{O}_n^{J/\psi}\rangle$ giving the probability for the $c\bar{c}$ pair to form a J/ψ meson; the $\langle\mathcal{O}_n^{J/\psi}\rangle$ describe the evolution of the $c\bar{c}$ pair into a J/ψ plus additional soft gluons. While in the Colour Singlet Model all c_n not corresponding to a colour singlet $c\bar{c}$ are set to zero, the NRQCD factorization formalism includes states where the $c\bar{c}$ system is a colour octet.

The colour octet long distance matrix elements have to be determined from fits to the data, and can be applied to obtain predictions for other processes, e.g. ψ production at HERA. Various groups have performed such fits (see fig. 1), and it turned out that the results depend heavily on non-perturbative effects like parton distibution functions, and the transverse momenta of the initial state partons. Today, we can only give order of magnitude estimates: it is probably safe to say that both the linear combination

$M_3 = \langle \mathcal{O}_8^{\psi}(^1S_0)\rangle + \frac{k}{m_c^2}\langle \mathcal{O}_8^{\psi}(^3P_0)\rangle$ (with $k \simeq 3$), and $\langle \mathcal{O}_8^{\psi}(^3S_1)\rangle$, which dominates at large p_T, are larger than 10^{-3} GeV^3.

In the NRQCD approach, the production of ψ mesons with $p_T \gg M_\psi$ is dominated by gluon fragmentation, and it is predicted that the gluon's transverse polarization is preserved as the $c\bar{c}$ pair evolves into a bound state. This leads to the prediction that directly produced ψ mesons will be increasingly transversely polarized at high p_T [6]. On the other hand, the Colour Evaporation Model predicts an absence of polarization [7]. Recently CDF has published polarization measurements based on all Run 1 data. The measurement of the polarization of J/ψ and ψ(2S) mesons is made by analyzing their decays to $\mu^+\mu^-$ in the helicity frame, in which the spin quantization axis lies along the ψ direction in the $p\bar{p}$ centre-of-mass frame. The angle θ is given by the direction of the μ^+ in the ψ rest frame and the ψ direction in the $p\bar{p}$ centre-of-mass frame. The angular distribution $I(\theta)$ is parameterized as $I(\theta) \propto 1 + \alpha \cos^2\theta$. Unpolarized ψ mesons have $\alpha = 0$ while $\alpha = +1$ or -1 correspond to fully transverse or longitudinal polarizations.

The method of determining α is to fit the observed distributions of $\cos\theta$ to distributions derived from simulated $\psi \to \mu^+\mu^-$ decays. In order to extract the polarization parameter α for promptly produced ψ mesons, the prompt component is separated from the B-decay component using the proper decay length of each event. In fig. 2 the CDF fit results for α as a function of p_T are compared with a theoretical NRQCD prediction. For both the J/ψ and $\psi(2S)$ states, no increasing transverse polarization at $p_T \geq 12\,$GeV is observed, in disagreement with NRQCD factorization predictions, although the uncertainties are too large to draw definitive conclusions.

2.2 χ_c

Using $\sim 18\,\mathrm{pb}^{-1}$ of data from Run Ia, CDF studied [2] the reaction $p\bar{p} \to \chi_c$X; $\chi_c \to J/\psi\gamma$. For $p_T(J/\psi) > 4$ GeV and $|\eta(J/\psi)| < 0.6$ the fraction of J/ψ mesons originating from χ_c meson decays is found to be $29.7 \pm 1.7(\mathrm{stat}) \pm 5.7(\mathrm{syst})\,\%$, not including contributions from b hadrons, and approximately independent of $p_T(J/\psi)$. Taking into account the measured fraction of prompt J/ψ mesons from $\psi(2S)$ decays ($7 \pm 2\,\%$ at $p_T(J/\psi) = 5$ GeV to $15 \pm 5\,\%$ at $p_T(J/\psi) = 18$ GeV), the fraction of directly produced J/ψ is $64 \pm 6\,\%$, approximately independent of $p_T(J/\psi)$. Direct J/ψ production is the largest

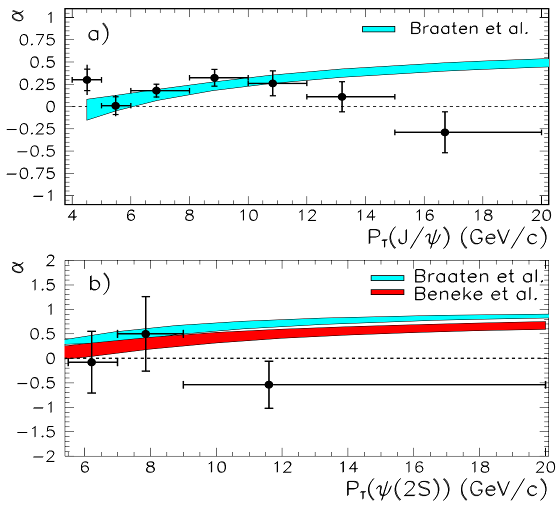

Figure 2: *The fitted polarization of J/ψ and $\psi(2S)$ mesons from prompt production, for $|y^{\psi}| < 0.6$. The shaded bands show NRQCD predictions which include for J/ψ the contribution from χ_c and $\psi(2S)$ decays.*

source of prompt J/ψ mesons.

CDF has also measured [8] the relative rate of production of the charmonium states χ_{c1} and χ_{c2} through their decay into $J/\psi\gamma$ using all Run 1 data. The photon from the decay is reconstructed through conversion into e^+e^- pairs, which makes the resolution of the two states possible. The ratio of production cross sections is found to be $\sigma_{\chi_{c2}}/\sigma_{\chi_{c1}} = 0.89 \pm 0.33(\mathrm{stat})^{+0.13}_{-0.10}(\mathrm{syst})$ for events with $p_T(J/\psi) > 4.0$ GeV, $|\eta(J/\psi)| < 0.6$ and $p_T(\gamma) > 1.0$ GeV, which is in agreement with NRQCD predictions.

2.3 Production and Polarization of Υ Mesons

A preliminary measurement [9] by CDF using Run 1b data of the differential cross section in p_T for $\Upsilon(1S, 2S, 3S)$ has been used to extract the relevant colour octet matrix elements [10]. They cannot yet be compared to other measurements, but can be used for predictions, e.g. for other $b\bar{b}$ states. A polarization analysis [9] on the $\Upsilon(1S)$ data sample in a similar way to that on the ψ sample resulted in $\alpha = -0.08 \pm 0.09$ for $2 < p_T < 20$ GeV and $|y(\Upsilon(1S))| < 0.4$. The measurement of the $\Upsilon(1S)$ polarization has the advantage of not having to separate the prompt decays from the B decays, but it is still statistics limited.

3 Inelastic J/ψ Production at HERA

The cross section of inelastic J/ψ production at HERA can also be calculated within the framework of NRQCD. Theoretical predictions and measurements exist in the photoproduction domain ($Q^2 \simeq 0$) and for deep inelastic scattering ($Q^2 \gtrsim 2$ GeV^2). In most cases, the elasticity variable z is used to separate diffractive and non-diffractive processes. In the proton rest frame, the elasticity z is the fraction of the photon energy transferred to the J/ψ. Unfortunately the z distribution of colour octet contributions is theoretically difficult to predict, since the perturbative expansion breaks down when the ψ takes close to its maximally possible energy, i.e. $z \simeq 1$. Diffractive production dominates for $z \simeq 1$.

3.1 J/ψ Production at "medium" z

In the medium z region, $0.3 < z < 0.9$, direct photon gluon fusion is expected to dominate the inelastic J/ψ production. In fig. 3 a) the $\gamma\, p$ cross section as a function of W is compared to a NLO calculation in the Colour Singlet Model. To exclude regions of big theoretical uncertainties, the restricted kinematic region $z < 0.8$ and $p_T > 1$GeV is shown here. The differential cross sections as a function of p_T^2 (b) and of z (c) show good agreement with the NLO calculations for $p_T^2 > 1$ GeV^2. In d) the z dependence of the cross section is compared to a NRQCD prediction, where the hard subprocess was calculated in LO and the matrix elements were extracted from CDF data, estimating higher orders with the help of a Monte Carlo simulation. The dotted line shows the colour singlet term, the dashed lines the additional colour octet terms for two sets of matrix elements, and the full lines the total predictions. A normalization factor of ~ 3 is needed to describe the data. In the medium z range the expected colour octet contributions are small, while at very low (resolved photon) and very high z the differences to the colour singlet model are much bigger.

In an analysis of inelastic J/ψ production in deep inelastic scattering based on 27 pb^{-1} of data collected in 1995 to 1997, H1 [11] has avoided the use of the theoretically unsafe z variable to define the inelastic cross section, and instead used the mass of the produced hadronic final state. The differential cross sections in Q^2, p_T^2, z, and y^* (the J/ψ rapidity in the $\gamma\, p$ centre-of-mass frame), are not well described [11] by a NRQCD prediction [12] with matrix

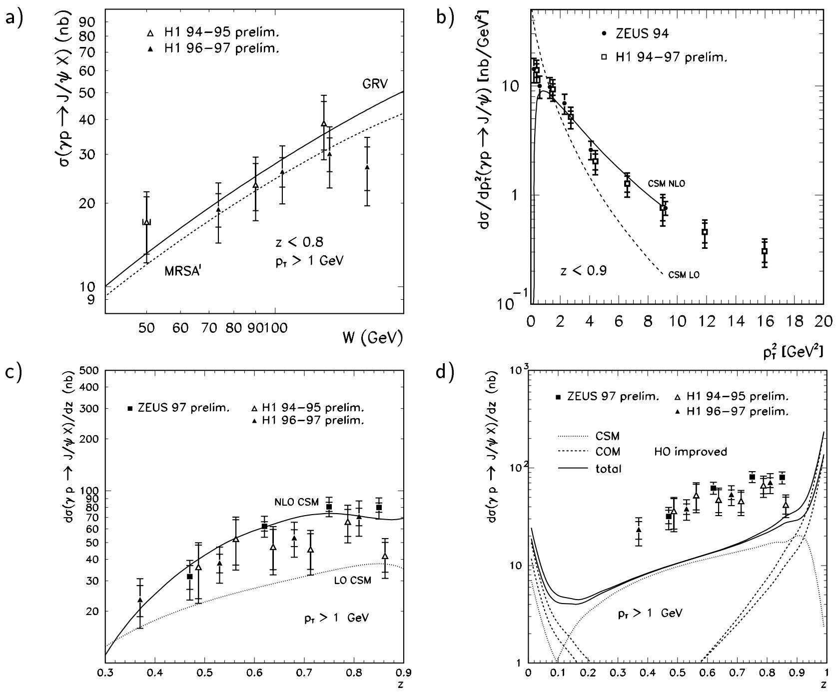

Figure 3: *a) Inelastic J/ψ cross section at intermediate z as a function of W. Differential cross sections in b) p_T^2 and c),d) z. The data* [13] *are compared to predictions of the Colour Singlet Model and calculations of colour octet contributions.*

elements extracted from CDF data. Leaving the colour octet matrix elements as free parameters, the H1 data are well described (fig. 4 a). Including an estimate of higher order corrections in the matrix elements extracted from CDF data, the H1 and CDF matrix elements are compatible [14] (fig. 4 b). Note that the H1 data have little sensitivity on $\langle \mathcal{O}_8^{\psi}(^3S_1) \rangle$, and are statistically limited, in part since the fit was restricted to the theoretically safe region in Q^2 and p_T^2.

3.2 Photoproduction of J/ψ at small z

In the region of low elasticity z resolved photon processes are expected to dominate in J/ψ photoproduction. H1 has presented a preliminary analysis [15] of this region. The detector acceptance currently limits the analysis to high values of W, therefore the data are not directly comparable to measurements at

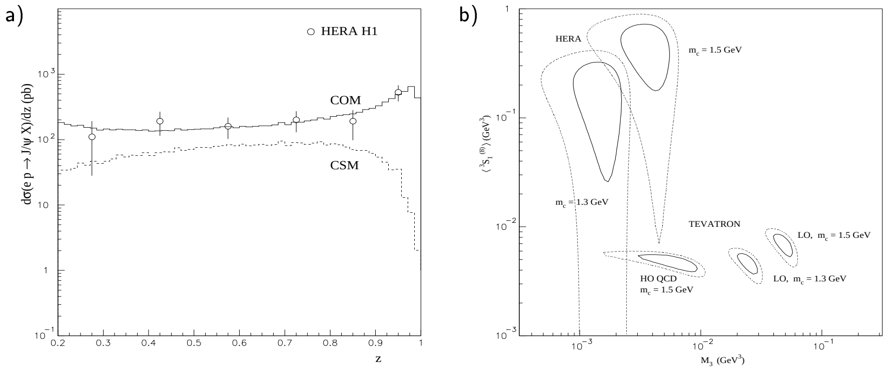

Figure 4: *a) H1 data on $d\sigma/dz$ in inelastic J/ψ production in DIS; b) parameter space for the colour octet NRQCD matrix elements. The bounds show the* $68\,\%$ *C.L. and* $95\,\%$ *C.L. Figures are from* [14].

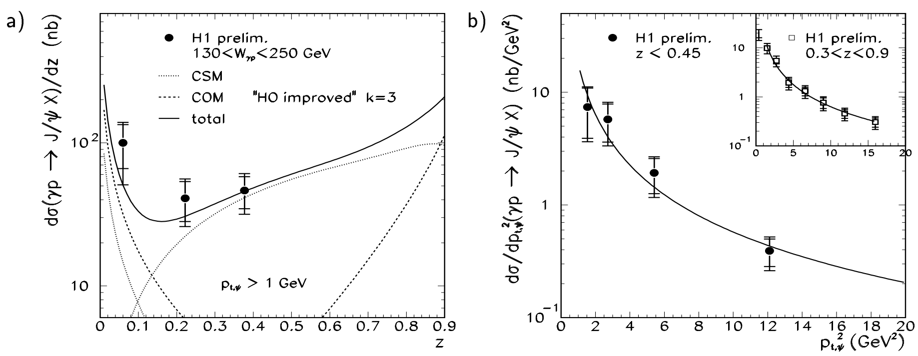

Figure 5: *Differential cross sections in a) z and b) p_T^2 for low z J/ψ production.*

medium z. The most important contribution to the resolved photon processes comes from gluon gluon fusion, quark induced processes are currently negligible. The measured differential cross section in z is shown in fig. 5 a. Although the low z data are not precise enough to distinguish between different predictions, this is the first indication for resolved photon J/ψ production. For the colour octet prediction, the matrix elements were extracted from CDF data, and higher orders were estimated with the help of a Monte Carlo simulation. The dotted line shows the colour singlet term, the dashed line the additional colour octet terms and the full line the resulting sum. The differential cross section as a function of p_T^2 is shown in fig. 5 b, together with a fit to the medium z data. The low z data are consistent with the medium z measurement.

4 Elastic J/ψ Production at HERA

At HERA, vector mesons can be produced elastically (exclusively), i.e. in the reaction $ep \to eVp$, where V denotes the vector meson, and the proton remains intact. The largest background is the proton dissociative process where the proton breaks up into a low mass system. H1 and ZEUS have developed efficient procedures to remove and correct for this and other backgrounds.

There is by now no doubt that perturbative QCD can describe the elastic production of vector mesons [16, 17] through the exchange of a colour neutral system of gluons, i.e. in leading order via exchange of two gluons. The QCD scale can be given by the mass of the vector meson, as in the case of the J/ψ, or by Q^2 as for the "light" vector mesons ρ, ω, and ϕ. The role of the momentum transfer t between incoming and outgoing proton (or the outgoing dissociated proton) as a hard scale is still under experimental investigation. A signature for the "hard" behaviour is the fast rise with W of the total γp cross section for vector meson production.

4.1 Total Cross Sections

Photoproduction of J/ψ mesons has been measured by the H1 collaboration [18] in the range $26 \leq W \leq 285\,\mathrm{GeV}$, and a preliminary measurement by ZEUS [19] covers a comparable domain. Leptonic decays into e^+e^- or $\mu^+\mu^-$ are used depending on the detector region. The data, based on an integrated luminosity of $10-28\,\mathrm{pb}^{-1}$ (H1) and $38-48\,\mathrm{pb}^{-1}$ (ZEUS), are shown in fig. 6, and are compared with results from pQCD calculations [16, 17] using various gluon density functions. The main prediction concerns the slope of the data, while there are significant normalization uncertainties. The same models also give a reasonable description of measurements in deep inelastic scattering [11], see fig. 6 (right). A fit to the photoproduction data of the form W^δ yields [18] $\delta = 0.83 \pm 0.07$ which is much larger than $\delta \simeq 0.2-0.3$ found in soft processes.

4.2 Determination of the Regge Trajectory for J/ψ Photoproduction

In order to determine the properties of the exchange mediating the interaction between the J/ψ meson and the proton, Regge language can be used. The Regge trajectory $\alpha(t)$ has been determined by ZEUS [19] and H1 [18] for photoproduction of J/ψ mesons. The measurements use the dependence of the

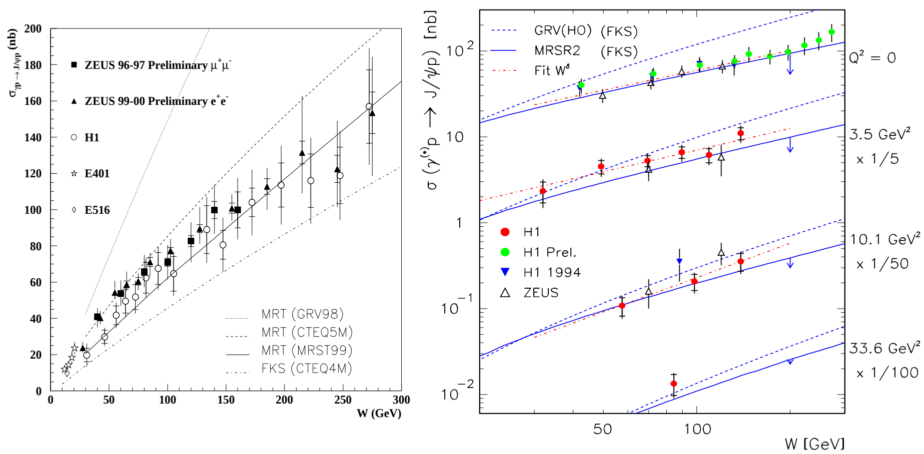

Figure 6: *Total cross sections for $\gamma p \rightarrow J/\psi\, p$ as a function of W in photoproduction only (left) and for various values of Q^2 (right). Predictions from pQCD based calculations are given using various gluon density distributions.*

cross section $d\sigma/dt$ at fixed values of t on the energy W as $W^{4(\alpha(t)-1)}$. Assuming a linear form $\alpha(t) = \alpha_0 + \alpha' t$, α' is expected to be small in "hard" interactions [16], while in "soft" reactions $\alpha' \simeq 0.25\,\mathrm{GeV}^{-2}$ has been found [20]. The new H1 and ZEUS measurements use data from one experiment only and thus avoid normalization problems between data from different experiments. A linear fit to $\alpha(t)$ yields the parameters of the fitted trajectory (see fig. 7 left). The slope (ZEUS [19]: $\alpha' = 0.11 \pm 0.03\,\mathrm{GeV}^{-2}$) turns out to be smaller than expected for soft processes, confirming that a significant fraction of elastic J/ψ production is a hard process.

4.3 The Scale for Exclusive Vector Meson Production

If in elastic vector meson production the photon couples to quarks (as opposed to coupling to a hadron), and the interaction of the quark pair of the vector meson with the proton is universal, the ratio of cross sections should only depend on the quark content of the vector mesons. This has indeed been observed at HERA, where at large Q^2 (much larger than the mass squared of the vector meson) the ratio σ_ϕ/σ_ρ is seen to approach the value of 2/9 expected from the simple SU(4) quark counting. The ratio $\sigma_{J/\psi}/\sigma_\rho$ increases slowly and is still below the expected value of 8/9 at $Q^2 \simeq 40\,\mathrm{GeV}^2$, but the uncertainties

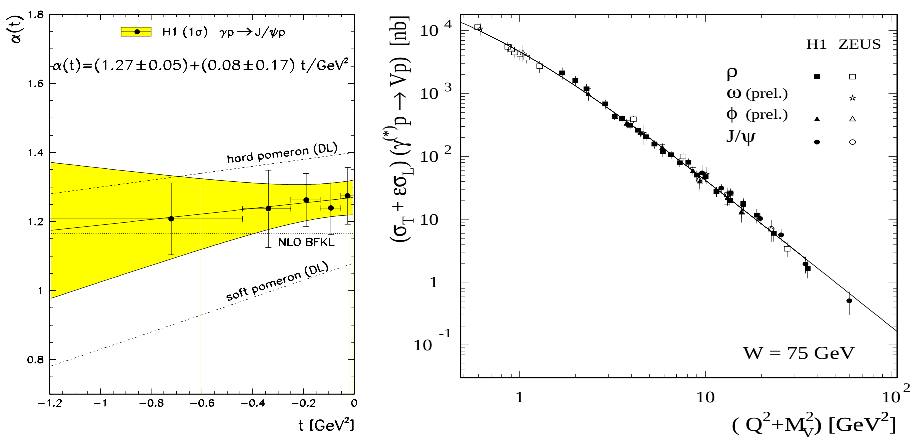

Figure 7: *Left: The measured Regge trajectory for the process $\gamma p \to J/\psi\, p$. The solid line shows the result of the fit. Also shown are the soft and the hard Donnachie-Landshoff pomeron trajectories* [20] *and the result of a NLO BFKL calculation* [21]*. Right: The total cross sections* [22] *for vector mesons scaled by the SU(4) ratios as a function of $Q^2 + M_V^2$.*

are still large. A universal behaviour of the cross section for all vector mesons is observed [22] in fig. 7 (right), where all available HERA data for ρ, ω, ϕ, and J/ψ mesons are shown as a function of $Q^2 + M_V^2$. The data have been scaled to a common $W = 75\,\text{GeV}$ using the measured W dependencies. They have been scaled by the quark charges according to $\rho : \omega : \phi : J/\psi = 9 : 1 : 2 : 8$. The data are seen to agree well with each other and can be described by a function $(Q^2 + M_V^2 + a)^b$ with $a = 0.42 \pm 0.09\,\text{GeV}^2$ and $b = -2.37 \pm 0.10$, which was obtained from a fit to ρ data. Within present errors $Q^2 + M_V^2$ is a good scale for the elastic production of vector mesons at low values of $|t|$.

5 Summary

Thanks to large efforts, both experimentally and theoretically, we have today a much better understanding of the mechanisms that govern the production of Quarkonia. I could only present a small selection of results from this very active field of current research. Both the Tevatron and HERA experiments will start collecting more data with upgraded detectors in 2001, allowing them to shed more light on the production of Quarkonia in the future.

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